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Digital Aerial Triangulation in Production - Experiences with Block Switzerland

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ABSTRACT

Digital aerial triangulation is increasingly being carried out in photogrammetric production environments as greater efficiency is being attained through increased automation. In this paper, a customised and modified approach to digital aerial triangulation using the Helava Automated Triangulation System (HATS) is introduced. HATS is used as the basic triangulation measurement tool for the aerial triangulation of the *swissphoto* block of more than 6000 images covering the entire area of Switzerland with photo scales varying from 1: 22'000 to 1: 54'000.
For the whole block Switzerland, aerial triangulation was performed from October 1995 until July 1998 in 43 sub-blocks using between 82 to 333 images per block. The results of seven selected triangulation sub-blocks are presented. Furthermore, the limitations of digital triangulation in difficult terrain as given in Switzerland, especially in alpine regions, are summarised and suggestions for improvements are discussed.

1. INTRODUCTION

The transition from analytical to digital photogrammetry has already been established in private photogrammetric companies. One of the major advantages of digital photogrammetry is the potential to automate production processes efficiently, thus substantially improving the price/performance ratio for photogrammetric products. Today, the key to an efficient photogrammetric production environment is the degree of automation in data production processes.

Image processing and computer vision techniques have successfully been employed for facilitating automated procedures in digital aerial images such as interior orientation (Schickler, 1995; Lue, 1995; Kersten and Haering, 1997a), relative orientation (Schenk et al., 1990), point transfer in photogrammetric block triangulation (Tsingas, 1992), and the generation of Digital Terrain Models (Krzystek, 1991).

Digital aerotriangulation including image import and image minification, interior orientation, point transfer, control point measurements, bundle block adjustment and quality control, is one of the most complex processes in digital photogrammetry and the automation of this process was one of the challenges in the photogrammetric community in the early nineties.

Investigations in automatic digital aerotriangulation have been performed in scientific institutions like Ohio State University (Agouris and Schenk, 1996; Toth and Krupnik, 1996) and University of Stuttgart (Tsingas, 1992; Ackermann and Tsingas, 1994), by system providers like LH Systems (DeVenecia et al., 1996) and Zeiss (Braun et al., 1996), and by software providers like Inpho, Stuttgart (Krzystek et al., 1996; Krzystek, 1998). Currently, there are a few software packages for automatic digital aerial triangulation commercially available: Helava Automated Triangulation System HATS (LH Systems), PHODIS-AT (Zeiss), MATCH-AT (INPHO and Intergraph), and since 1999 IMAGINE OrthoBASE (Erdas), ORIMA/APM on NT (LH Systems), and Virtuozo. But only few users (Kersten and Stallmann, 1995; Beckschaefer, 1996; Kersten and O'Sullivan, 1996b; Hartfiel, 1997; Kersten and Haering, 1997b; Kersten et al., 1998; Kaeser et al., 1999; Masala, 1999; Kersten, 1999b; Urset and Maalen-Johansen, 1999) have reported their experiences in digital aerotriangulation using a commercial photogrammetric system, although many systems are already in use world-wide. A comparison of different triangulation software packages is presented in Kersten (1999a).

Since 1995, Swissphoto Vermessung AG, the former Swissair Photo+Surveys Ltd., is using digital photogrammetric stations from LH Systems (LHS). For the project *swissphoto* (Kersten and O'Sullivan, 1996a), a block of 6063 aerial images covering the entire area of Switzerland with a photo scale between 1: 22'000 and 1: 54'000 was triangulated from October 1995 until July 1998. Seven representative sub-blocks from the block Switzerland are presented in Chapter 2. The customisation and modification of the Helava Automated Triangulation System (HATS) through the implementation of additional software and graphical user interfaces (developed by Swissphoto Vermessung AG) is introduced in Chapter 3. This approach increases the automation and efficiency of the commercially available system in Swissphoto's digital photogrammetric production environment. Some results (Chapter 3) and the production rate (Chapter 4) of seven different blocks are presented. Furthermore, problems and limitations of digital triangulation,

Block	Area covered [km²]	Ground height [m]	Terrain characteristics	Photo scale (average)	Forward/Side overlap [%]	Date of flight (days)
Aargau	1262	350 - 900	agricult., hilly	~1: 28'200	70%/30%	June/July '95, (3)
Basel	1203	250 - 1300	urban, hilly	~1: 26'700	70%/30%	Jul./Aug. '95, (4)
Lucerne	1735	380 - 1800	hilly, mountain.	~1: 26'700	70-90%/10-30%	June/July '95, (4)
Nidwalden	3726	400 - 2900	alpine, lakes	~ 1:24'000 - 1: 40'000	70-90%/10-30%	Jul.-Oct. '95, Jul. '96 (9)
Thusis	1800	550 - 2900	alpine	~ 1:22'000 - 1: 52'000	70-90%/10-30%	Oct. '95 (7)
Brienz	2080	430 - 2650	alpine	~ 1:28'000 - 1: 40'000	70-90%/10-30%	Jul.-Oct. '95, Jul. '96 (7)
Lugano	3477	190 - 2600	alpine, lakes	~ 1:24'000 - 1: 51'000	70-90%/10-30%	Aug.-Oct. '95, Sep. '96 (7)

Table 1: Flight and block data of seven *swissphoto* triangulation sub-blocks

especially in difficult terrain as given in the Swiss alpine regions, are discussed and improvements for the digital triangulation software are suggested in Chapter 5.

2. TRIANGULATION BLOCKS AND PHOTOGRAMMETRIC SYSTEMS USED

2.1. Triangulation block Switzerland

For efficient triangulation, also with respect to the available hardware and software performance, block Switzerland was divided in 43 sub-blocks between 82 - 333 images per block. All sub-blocks were connected to each other with an overlap of three images in strip direction and one strip across strip direction.

For the project *swissphoto* (Kersten and O'Sullivan, 1996a), Switzerland was flown in three phases using colour and infra-red films simultaneously. Figure 1 illustrates the flight lines which were flown in 1995 and the perimeters of the

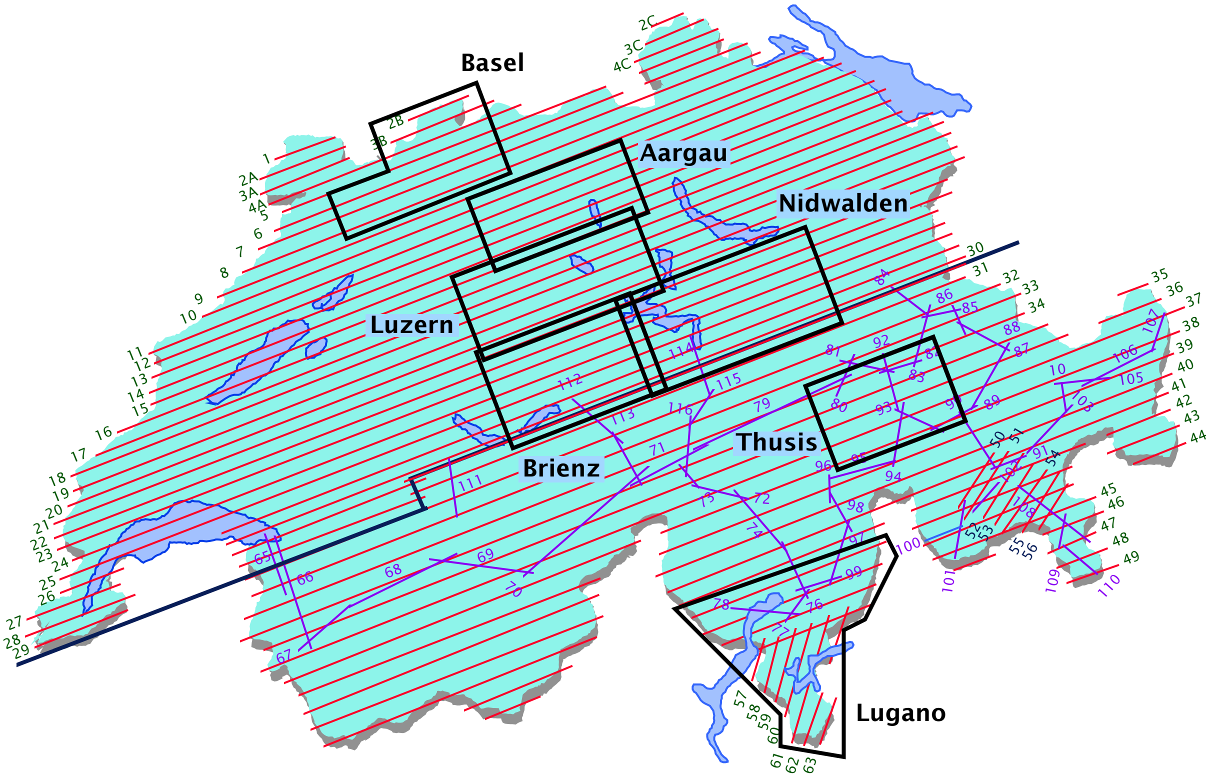

Figure 1: *swissphoto's* triangulation block Switzerland including seven selected sub-blocks

seven sub-blocks. In phase 1 the urban areas and the northern part of the country were flown between June and August; in phase 2 the Alps and all valleys in the southern part of the country were flown between August and October 1995, while in phase 3 some small areas of Switzerland were re-flown from July to September 1996 due to hazy and partly cloudy air conditions during the 1995 flight. The regular flight lines were flown from east to west as parallel flight lines and in the opposite direction with an azimuth of ~70 resp. 250 degrees. The valleys in the southern part were flown in the directions of the valleys. The photo scale was approximately between 1: 22'000 and 1: 28'000 in the non-mountainous areas including the separate flights in the southern valleys and between 1: 34'000 and 1: 55'000 in the Alps. During the flights, camera stations were recorded by DGPS using a Leica GPS receiver in the aircraft and at each of three reference stations on the ground. Additionally, 104 well distributed points of the new Swiss GPS primary network LV'95 were signalised as control points.

In this paper, seven triangulation sub-blocks of Block Switzerland are introduced, which represent different terrain characteristics and block size. Block Aargau consists of 152 images (6 strips, average photo scale 1: 28'200) and represents agriculture and hilly terrain characteristics with varying ground height between 350-900 m a.s.l. Block Basel has almost the same block size (150 images, 7 strips, photo scale 1: 26'700) as Block Aargau, but represents urban areas and hilly terrain characteristics with a varying ground height from 250 m to 1300 m. In block Lucerne (216 images, 7 strips, photo scale 1: 26'700) the terrain varies between hilly and mountainous (ground height from 380 m to 1800 m). These three sub-blocks represent the Swiss midland, while the following blocks represent mountainous and alpine terrain characteristics: Block Brienz (270 images, height differences between 450 m and 2600 m) consists of 11 regular flight lines and one strip from a valley flight, which causes large photo scale differences from 1: 22'000 to 1: 41'000. Block Thusis (185 images) includes five valley flight lines and five regular east/west strips with large photo scale differences from 1: 22'000 to 1: 52'000 (height differences between 430 m and 2900 m). Nidwalden is the biggest sub-block (333 images) of the all 43 *swissphoto* sub-blocks. Its terrain characteristics are similar to Block Brienz including the lake Lucerne. This block consists of 12 flight lines with a photo scale of approximately 1: 24'000 and one line with 1: 40'000. Four lines were flown in 1996 to replace images with clouds from 1995. Block Lugano (261 images) is the most southern block with 7 flight lines (photo scale 1: 27'000) in north-south direction, 7 lines (photo scale 1: 51'000) in east-west direction (four lines from 1996 with a photo scale of 1: 40'000), and 5 lines along the valleys (photo scale 1: 23'000). The area of this block is characterised by mountains, steep valleys and some lakes. The image quality of this block was not optimal due to hazy weather conditions during the flights. Furthermore, the recording of the GPS camera station data did not work successfully during the overflight of this area.

Each block includes flight lines with different exposure dates which varied from some days to more than 1 month up to 1 year (e.g. Block Nidwalden, Brienz and Lugano) and consequently vegetation changes from strip to strip are partly occurring. Flight and block data of the seven introduced *swissphoto* sub-blocks are summarised in Table 1.

2.2. Digital image data

In total 7081 colour images were scanned within the project *swissphoto* on a Digital Scanning Workstation DSW200 of LH Systems in RGB mode from August 1995 until January 1998. During seven months in 1996/1997, a second rented DSW200 was used in parallel production. For high quality scanning, the two scanners (XY stage) were installed in a separate room, containing air-conditioner, air-humidifier and a dust filter, to minimise dust and dirt on the photos and on the glass plate of the scanner. The turnaround time for scanning each photo was about 30 minutes using a SUN Sparc 20/71 in the beginning resp. 20 minutes using a SUN Ultra 1. The resolution of the images was 25 µm, which corresponds to a footprint of 0.6 - 1.3 m on the ground. For triangulation of the *swissphoto* sub-blocks, the digitised colour images were converted into greyscale images in order to reduce disk space usage. The file size of each greyscale image was about 80 Mbyte.

2.3. Hardware

The aerial triangulation was performed on a digital photogrammetric workstation DPW670 (Mono-station) of LH Systems (Fig. 2). As a computer platform a SUN Ultra 2 (167 MHz) was used. In total 105 GByte disc storage capacity was available for the triangulation data. Three sub-blocks in the southern part of Switzerland (St. Bernard, Zermatt and Maggia) were triangulated with Match-AT from Inpho (Stuttgart) on a Silicon Graphics (SGI O2, R5000) in order to test an alternative triangulation software package in production.

2.4. Software

For triangulation of all sub-blocks the software release 3.1.2, 3.2 and 4.0 of SOCET SET (Softcopy Exploitation Tools) was used. HATS is a module of SOCET SET for performing block triangulation of suitably overlapping images. The tedious process of selecting and measuring image coordinates of pass and tie points is highly automated, with the possibility of operator override. The system flags unacceptable tie points and displays the required images for

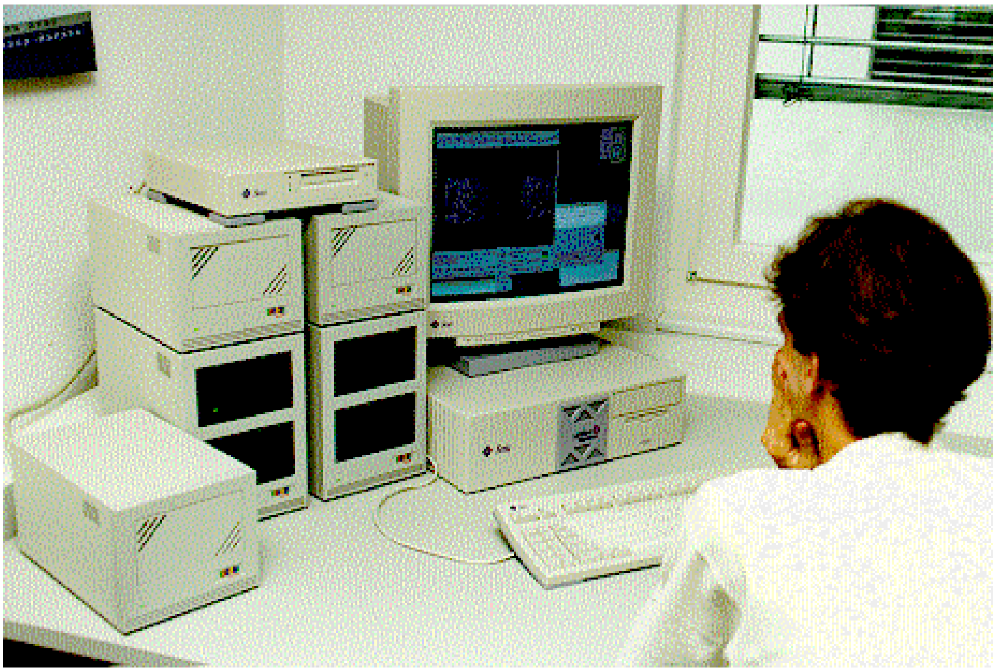

Figure 2: Digital aerial triangulation station at Swissphoto Vermessung AG

measurement without operator intervention. All the operator has to do is to re-measure these unacceptable points by moving the floating mark to their proper locations, if requested.

3. DIGITAL AERIAL TRIANGULATION

In an automated production, the digital aerial triangulation (AT) is divided into several processing steps, which include data preparation (photos and control points), automatic data import and image minification, automatic interior orientation, automatic AT measurements, GPS supported bundle block adjustment, and quality control. To facilitate the use of the highly automated AT processing modules by the operator, some additional software for batch processing and easy-to-use graphical user interfaces (GUIs) were developed by Swissphoto Vermessung AG.

3.1. Data preparation

The data preparation includes configuration of the photo block (providing images, loading digital images from tape, if not available on disk) and providing control point data (co-ordinates, overview plot, available sketches). To obtain sufficient ground control points, five different sources are used for all *swissphoto* blocks:

- signalised points from the new Swiss GPS primary network LV'95 (accuracy in xyz = 0.3m)
- points from additional GPS campaigns (accuracy in xyz = 0.3m)
- vertical control points from the 1: 10'000 Canton map series (accuracy in z = 1.5m)
- vertical control points from the Swiss 1: 25'000 map series (accuracy in z = 1.5m)
- horizontal control points from official cadastre maps (accuracy in xy = 0.5m)

The majority of the signalised control points in the southern part of Switzerland were destroyed before the flight could take place due to a long time period between signalisation and flights. Thus, many control points were subsequently determined by GPS measurements using well-defined points in the digital images. Ground control preparation for the *swissphoto* triangulation blocks was a very time consuming process, which varied from block to block. This part of the triangulation required the most intervention resp. preparation by the operator.

3.2. Automatic data import and image minification

Before starting the measurements, the image import into the photogrammetric station and the minification of the images (generation of image pyramid levels for measurements, display and zooming) were performed fully automatically in a batch mode, which took up to 60 seconds per image on the SUN Ultra 2. The GPS photo centre co-ordinates of each image were also automatically imported to provide approximate values for the overlaps between images in the blocks. Additionally, the preparation of the triangulation files which contain all parameters for the automatic measurements, were performed automatically. Thus, using such customisation, the operator input was significantly reduced in comparison to when using the non-enhanced commercial software package HATS.

3.3. Automatic interior orientation

Before starting HATS, the interior orientation must be determined for each image. To avoid the time consuming semi-automatic measurements of the interior orientation, a fully operational automatic interior orientation (IO) of digital aerial images was developed at Swissphoto Vermessung AG and integrated into SOCET Set on the DPW670/770. This operation can be performed in batch mode without any operator intervention. The IO of an unlimited number of images related to one specifically defined camera type can be automatically determined in one step including quality control. The speed of the measurements and IO determination is approximately 5 seconds per image. The algorithm used is described in Kersten and Haering (1997a).

3.4. Automatic AT measurements

The processes of AT measurements, as currently used in HATS, are divided into four steps which include Automatic Point Measurement (APM), Interactive Point Measurement (IPM), Simultaneous Solve (Re-measurements) and Blunder Detection.

Before running APM, a tie point pattern was selected and edited to obtain a well distributed point configuration in each image for connecting the block. A very dense tie point pattern consisting of 98 points was used as a standard pattern for all described blocks. APM runs as a batch process mostly overnight or during the weekend. APM takes approximately 10-30 minutes per image on the SUN Ultra 2. After APM, a rate of 64-94% successfully measured points could be achieved for the blocks, depending on the terrain characteristics, the variation in the photo scale within each block and flight date differences between strips (Aargau 94%, Basel 89%, Lucerne 80%, Nidwalden 53%, Brienz 64%, Thusis over 60%, Lugano 34-75% for APM in each single strip). The success rate of APM was clearly higher for blocks in the northern part of Switzerland.

Ground control points and additional tie points were measured with IPM in a semi-automatic mode. If the datum is fixed by measurements of three control points or by GPS camera stations, the program drives the operator to the approximate positions of the subsequent ground control points automatically.

The triangulation of most sub-blocks in the northern part of Switzerland could be performed with APM. If necessary due to bad connections of strips, additional points were measured manually with IPM in a semi-automatic mode. In sub-blocks with mountainous terrain and valley flight lines the success rates of APM were often so bad that it was decided to measure all these blocks with a new strategy: APM was performed for each flight line and the lines were connected by manual measurements of additional tie points with IPM in a semi-automatic mode. The manual connection of these strips was time-consuming. The problem of APM failure in sub-blocks with mountainous area and additional valley flight lines can be attributed to extreme height differences and to the large photo scale differences between the valley flight lines and the regular strips.

After all measurements were performed, the observations were adjusted using the „Simultaneous Solve“ module of HATS. Instead of re-measuring all errors, a rigid blunder detection routine, which was developed by Swissphoto, eliminates all observations with residuals over a user-specified threshold. Simultaneous solve and blunder elimination were performed in an iterative mode until a certain specified precision was obtained. This blunder detection uses only an user-specified threshold criterion and assumes high redundancy in the observations. But with this method it happened that too many observations, especially between strips, were eliminated due to bad quality points from APM. Nevertheless, areas of weak block connections were detected later in the quality control, and gaps without any points had to be filled-in by semi-automatic measurements. Unfortunately, simultaneous solve was often disturbed by so called „pseudo“ observations, where the system tried to connect images to each other without overlap (software release 3.2). These gross errors influenced all other observations significantly and it was always time consuming to remove all these blunders. As a better quality control solution, the computations of spatial intersection for each point would clearly indicate big blunders for subsequent automatic elimination, which is not yet implemented in HATS.

3.5. Bundle block adjustment

After a rough adjustment in HATS with simultaneous solve, all measured image co-ordinates of each sub-block were exported in a PATB-format and transferred from the DPW670 to a PC, where the bundle block adjustment was performed for each sub-block. All observations (image co-ordinates, control point co-ordinates and GPS photo centres) were adjusted in a bundle block adjustment with self-calibration using the bundle block adjustment program BLUH of the University of Hannover. After each run of the bundle block adjustment, an additional automatic blunder elimination was performed to eliminate all image points with residuals over a specified threshold (e.g. over 30 microns).

Block	Images	Strips	Control H/V	Max. rays per point	σ_0 [μm]	RMS X [m]	RMS Y [m]	RMS Z [m]	RMS X_0 [m]	RMS Y_0 [m]	RMS Z_0 [m]
Aargau	152	6	12/107	8	12.2	0.45	0.44	0.79	0.48	0.40	0.18
Basel	150	8	80/159	7	11.5	0.59	0.62	0.78	0.37	0.31	0.11
Lucerne	216	8	22/144	7	11.8	0.55	0.64	1.01	0.59	0.57	0.13
Nidwalden	333	13	11/180	23	11.5	0.60	0.39	1.24	0.44	0.35	0.13
Thusis	185	11	10/108	29	12.6	0.45	0.35	1.25	0.29	0.22	0.36
Brienz	270	12	13/128	19	11.7	0.26	0.31	1.04	0.47	0.34	0.13
Lugano	263	19	13/137	26	12.4	0.88	0.57	1.96	0.24	0.49	0.22

Table 2: Results of the bundle block adjustments of seven *swissphoto* sub-blocks

The results of the adjustments are summarised in Table 2. For the seven *swissphoto* blocks the root mean square (RMS) values of the control point co-ordinates are between 0.3 m and 0.9 m in X and Y, and between 0.8 and 2 m in height, while the RMS values of the station co-ordinates are better than 0.6 m in X and Y, and better than 0.4 m in Z. The σ_0 from the adjustment varies between 11.5 and 12.6 micron, which corresponds to approximately 1/2 of the pixel size. These results are representative for all other blocks measured with HATS. For the three sub-blocks measured with Match-AT, σ_0 from the adjustment varies between 6.1 and 7.7 micron, which corresponds to precision of approximately 1/4 to 1/3 of the pixel size.

The level of precision of digital AT with automatic point transfer depends significantly on the matching algorithm applied. With feature based matching a precision of 0.3-0.5 pixels can be assumed for point transfer, while with least squares matching a precision of 0.1-0.2 pixels can be achieved. More details about accuracy considerations of digital AT are contained in Ackermann (1996). A precision of 1/2 of the pixel size was achieved with the *swissphoto* sub-blocks using the cross correlation algorithm in SOCET SET (see Table 2). The reasons for the results achieved with these *swissphoto* sub-blocks could be addressed to bad ground control quality (especially the height control from the maps) and the large number of measurements (many tie points with bad quality) in each block, which also include points with residuals larger than one pixel (25 μm). However, the large number of measured points per image and their good distribution in the image provide a high reliability in the adjusted camera station co-ordinates. The results from triangulation were used for digital orthophoto production.

3.6. Quality control

After the final bundle adjustment, an update of the orientation data for each image support file and the measured image point files is performed at the DPW670 using interfaces between BLUH and SOCET SET. The geometric quality control for the block is given by the results of the bundle adjustment (σ_0, RMS, etc.). Furthermore, due to high automation of the measurements and gross error elimination, it is absolutely essential to check the photo connections within each strip and across the strips, in order to confirm a reliable point distribution and connection in the triangulation block. Therefore, an additional software module was developed by Swissphoto Vermessung, which provides a fast and easy-to-use visualisation of all point connections in the block (Fig. 3). Using this module, the operator is able to scan quickly through the block, photo by photo and strip by strip, to check visually the number of rays per point, the distribution of points in each photo, and, by clicking on the photo number in the display window, the connections to each neighbouring photo. Thus, the operator is able to analyse the connections within the block and to measure additional points in weakly connected areas after the measurements (APM and IPM) and after the bundle block adjustment. In Figure 3, the following information is displayed: image perimeter of image 16_137, all measured points of image 16_137 (e.g. 4 indicates the number of rays, i.e. this point is connected to three other images), point position in image 16_137, all images connected to image 16_137 indicated as image number (e.g. 17_128). The operator checks the connections between images by clicking on one of the image numbers around the displayed image perimeter (e.g. 17_128) with the mouse. All points, which are measured in both images, are highlighted in blue colour in the displayed image perimeter.

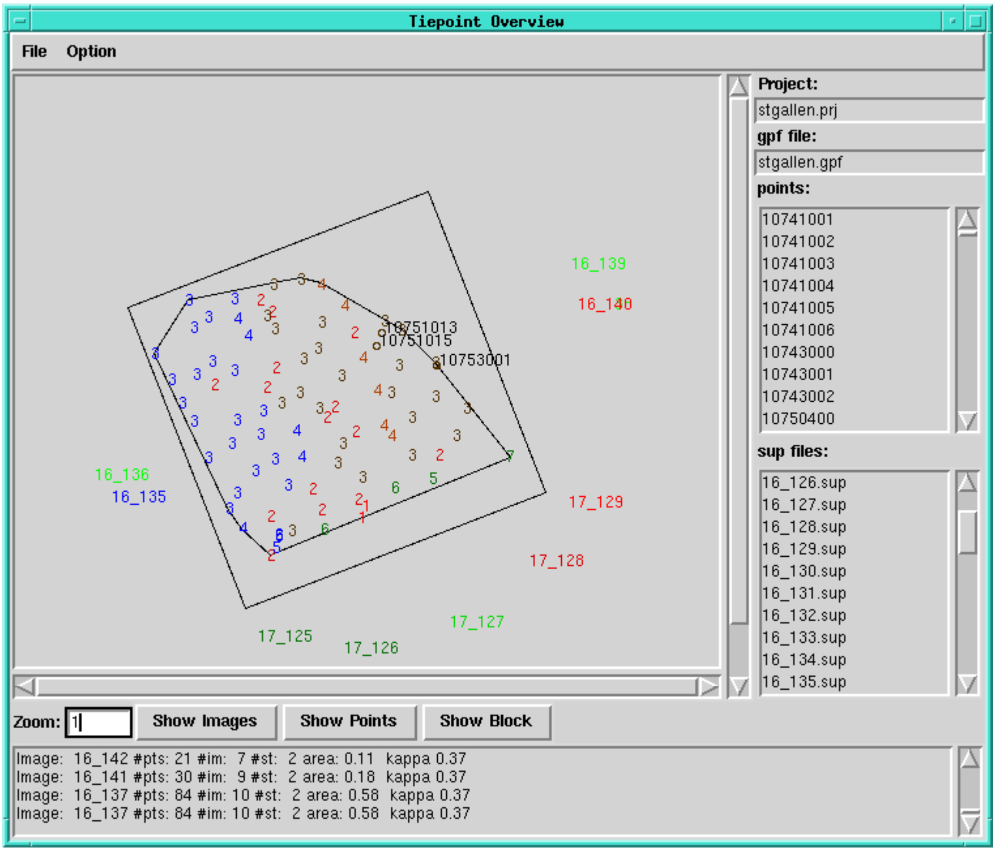

Figure 3: Quality control of aerial triangulation by visualisation of photo connections

4. TIME REQUIRED

The time required for digital aerial triangulation of each introduced block is summarised in Table 3. In this table, only the operator's time is counted, while the computation time of the computer for running batch processes, which is mostly done overnight, is neglected.

In our investigations for triangulation of the block Switzerland using HATS, a total time of 9 min per photo required for the triangulation of block Aargau, excluding scanning and ground control preparation, was the best result achieved. For the sub-blocks Aargau, Basel and Lucerne, a high degree of automation was achieved through successful automatic point transfer, due to good terrain characteristics in these blocks and little interaction of the operator in the data processing and quality control.

A slightly worse result (16 to 38 min per image) with respect to efficiency was achieved with the *mountainous* sub-blocks Nidwalden, Brienz, Thusis and Lugano. The problems of these blocks for the automatic point transfer were: (a) extreme height differences in the alpine region (steep valleys), (b) photo scale differences between strips, (c) the time intervals between the flight dates of the strips (up to one year), and (d) strip overlap sometimes less than 10%. The production rate of other *swissphoto* sub-blocks was sometimes worse.

The productivity rate obtained with these seven triangulation blocks is significantly worse in comparison to the results achieved with the triangulation of other Swiss blocks. Krzystek (1998) reports about the triangulation of a Swiss block (400 b/w images, scale ~1: 30'000, area Bern-Fribourg-Interlaken) in mountainous terrain using MATCH-AT. For this block, a production rate of better than 5 minutes per photo (operator time) was achieved. However, other authors, Kaeser et al. (1999) and Urset and Maalen-Johansen (1999), report that a similar production rate for triangulation in alpine and Nordic terrain was achieved using Match-AT compared to the aforementioned production rate of the *swissphoto* sub-blocks using HATS (see Table 3).

Other authors report good productivity for digital triangulation in flat terrain. DeVenecia et al. (1996) report a total working time of around 10 minutes per image, which was achieved with two test blocks using HATS. The two test blocks (Forssa and Wisconsin) have a photo scale of around 1: 4'000 and represent a very flat area with maximum height differences of 10 meters. Beckschaefer (1996) reports about 66 images per eight hour shift as the best result for digital aerotriangulation on the INTERGRAPH ImageStation, which corresponds to a production rate of 7.3 minutes per image.

AT processing steps/Blocks	Aargau	Basel	Lucerne	Nidwalden	Thusis	Brienz	Lugano
Preparation [h]	4.0	5.0	7.5	12.5	20.0	9.0	13.5
AT Measurements [h]	13.0	16.5	29.0	69.5	90.0	78.5	57.0
Bundle block adjustment [h]	5.0	3.0	7.0	6.5	7.5	15.0	4.0
Total elapsed time [h]	22.0	24.5	43.5	88.5	117.5	102.5	74.5
Number of images	152	150	216	333	185	270	263
Elapsed time per image [min]	8.7	9.8	12.0	15.9	38.0	22.8	17.0

Table 3: Elapsed time for digital AT using a customised and modified approach of HATS

5. ALGORITHMIC ASPECTS

The quality of the results and the efficiency of triangulation are dependent on the quality of automatic point transfer and correlation (measurement algorithm), which again depend mainly on image quality (including scanning and weather conditions) and terrain characteristics (e.g. land-cover and height differences). In summary, the following aspects caused problems for the correlation algorithm in our investigations:

- Extreme height differences in the images resp. block
- Strips with different flight dates (vegetation changes in summer)
- Shadows from early morning flights (bad quality terrain representation)
- Densely forested areas and lakes
- Triangulation blocks with variable photo scale within the block (from strip to strip)

To improve HATS with respect to speed, precision, robustness, flexibility, and user-friendliness the following software improvements are suggested:

(1) An easy-to-use GUI for providing and checking initial orientation values of images to build the triangulation block including the overlap of each image. The success rate of APM depends significantly on good initial values for the image orientation.

(2) The use of an existing DTM (Digital Terrain Model) in APM speeds up the APM process and increases the precision and robustness significantly, especially in mountainous and alpine regions, so that the rate of successfully measured points can also be increased.

(3) The implementation of a combined matching technique using feature based matching for rough measurements in low image pyramid levels and least squares image matching for precise measurements improves the precision of the overall measurements slightly. A small disadvantage due to slightly reduced speed should be ignored due to the increasing performance of each computer generation.

(4) The use of GPS data, additional parameters and an efficient band ordering algorithm for the re-linearisation of the normal equation system in simultaneous solve provides better approximations and accuracy, more flexibility and speed-up of the adjustment module.

(5) The use of on-line quality control by computation of spatial intersections of the measured points after the measurements reduces the number of blunders significantly.

(6) The integration of bundle block adjustment or the use of on-line triangulation algorithms (sequential estimation in bundle block adjustment and data snooping in blunder detection) during APM to increase the quality of the automatic point measurements through elimination of gross errors during the measurement phase (Gruen, 1985a).

6. CONCLUSIONS AND OUTLOOK

For the block Switzerland with more than 6000 images, digital aerial triangulation using HATS has been successfully performed in terrain with varying characteristics. During the aerial triangulation processing of the 43 sub-blocks, the commercial triangulation software used was customised and modified by development of additional software and GUI's to obtain a higher degree of automation in the workflow of digital aerial triangulation and to reduce the intervention of the operator to a minimum.

However, it could be also shown that the production rate for triangulation in alpine regions is much worse than in flat or non-difficult terrain. This demonstrates that the production rate resp. the efficiency of digital aerial triangulation is mainly dependent on the type of the terrain and the block configuration. In particular, the variation of the photo scale within the block and extreme height differences in terrain like the Swiss Alps cause problems to the correlation algorithm. This leads to a bad performance in the automatic point transfer. To fulfil the requirements for successful digital triangulation in difficult terrain, improvements of the automatic point transfer approach must be done. E. g., the use of an initial DTM and an on-line triangulation algorithm including quality control could reduce the problems in automatic point transfer. But a major problem for the automatic point transfer, the variation of the photo scale, will still occur, which might require interactive point measurements in semi-automatic mode.

However, we believe that, in general, there is potential for more improvements in digital AT with respect to productivity so that a triangulation rate of better than 5 minutes per image could be possible in the future, even with difficult terrain characteristics as in the Swiss Alps. Currently, it seems that analytical aerial triangulation is still competitive to digital AT in difficult terrain like in the Swiss Alps, if also variable photo scales occur in the blocks.

Today, the integration of bundle block adjustment in the automatic point transfer module is the modern trend, but is not implemented in all commercial triangulation software packages. The automation in digital aerial triangulation must include automatic quality control to obtain high reliability and efficiency. Nevertheless, direct measurement of exterior orientation by GPS and Inertial Measurement Units (e.g. Applanix system, Lithopolous, 1999) will be increasingly performed during aerial flights. But it can be assumed, that the combination of digital aerial triangulation and direct measurement of exterior orientation by GPS/INS will be a good solution for reliability reasons and quality control.

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